

D mesons in asymmetric nuclear matter at finite temperatures

Arvind Kumar* and Amruta Mishra†

*Department of Physics, Indian Institute of Technology,
Delhi, Hauz Khas, New Delhi – 110 016, India*

Abstract

We study the in-medium properties of D and \bar{D} mesons in isospin-asymmetric nuclear matter at finite temperatures using an effective chiral $SU(4)$ model. The interactions of D and \bar{D} mesons with nucleons, scalar isoscalar meson σ , and scalar iso-vector meson δ are taken into consideration. It is found that as compared to the \bar{D} mesons, the properties of the D mesons are observed to be quite sensitive to the isospin-asymmetry at high densities. At finite densities, the masses of D and \bar{D} mesons observed at finite temperatures are seen to be higher in comparison to the zero temperature case. The present study of the in-medium properties of D and \bar{D} mesons will be of relevance for the experiments in the future facility of the FAIR, GSI, where the compressed baryonic matter at high densities and moderate temperatures is expected to be produced. The mass modifications of D and \bar{D} mesons in hot nuclear medium can lead to decay of the charmonium states (Ψ' , χ_c , J/Ψ) to $D\bar{D}$ pairs in dense hadronic matter. The isospin-asymmetric effects on the properties of the open charm mesons for the doublets $D = (D^0, D^+)$ and $\bar{D} = (\bar{D}^0, D^-)$ should show in observables like their production and collective flow in asymmetric heavy-ion collisions. The small attractive potentials observed for the \bar{D} mesons may also lead to formation of the \bar{D} mesic nuclei.

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*Electronic address: iitd.arvind@gmail.com

†Electronic address: amruta@physics.iitd.ac.in, mishra@th.physik.uni-frankfurt.de

I. INTRODUCTION

The study of in-medium properties of hadrons is important for the understanding of strong interaction physics. The study of in-medium hadron properties has relevance in heavy-ion collision experiments as well as in astro-physics. There have been also extensive experimental efforts for the study of in-medium hadron properties by nuclear collision experiments. In these heavy-ion collision experiments, hot and dense matter is produced. By studying the experimental observables one can infer about how the hadron properties are modified in the medium. For example, the observed enhanced dilepton spectra [1, 2, 3] could be a signature of medium modifications of the vector mesons [4, 5, 6, 7, 8]. Similarly the properties of the kaons and antikaons have been studied experimentally by KaoS collaboration and the production of kaons and antikaons in the heavy-ion collisions and their collective flow are directly related to the medium modifications of their spectral functions [5, 9, 10, 11, 12, 13, 14, 15]. The study of D and \bar{D} mesons properties will be of direct relevance for the upcoming experiment at FAIR, GSI, where one expects to produce matter at high densities and moderate temperatures [16]. At such high densities, the properties of the D and \bar{D} mesons produced in these experiments are expected to be modified which should reflect in experimental observables like their production and propagation in the hot and dense medium. The reason for an expected appreciable modifications of the D and \bar{D} mesons is that D and \bar{D} mesons contain a light quark (u,d) or light antiquark. This light quark or antiquark interacts with the nuclear medium and leads to the modifications of D and \bar{D} properties. The experimental signature for this can be their production ratio and also in-medium J/ψ suppression [17, 18, 19]. In heavy-ion collision experiments of much higher collision energies, for example in RHIC or LHC, it is suggested that the J/ψ suppression is because of the formation of quark-gluon plasma (QGP) [20, 21]. However, in Ref. [22, 23, 24] it is observed that the effect of hadron absorption of J/ψ is not negligible. Due to the reduction in the masses of D and \bar{D} mesons in the medium it is a possibility that excited charmonium states can decay to $D\bar{D}$ pairs [25] instead of decaying to lowest charmonium state J/ψ . Actually higher charmonium states are considered as major source of J/ψ [26]. Even at certain higher densities, it can become a possibility that the J/ψ itself will decay to $D\bar{D}$ pairs. So this can be an explanation of the observed J/ψ suppression by NA50 collaboration at 158

GeV/nucleon in the Pb-Pb collisions [20]. The excited states of charmonium also undergo mass drop in the nuclear medium [27]. The modifications of the in-medium masses of D mesons is large then the J/ψ mass modification [28, 29]. This is because J/ψ is made of heavy quarks and these interact with the nuclear medium through gluon condensates. The change in gluon condensates with the nuclear density is very small and hence leads to small modification of J/ψ mass.

The in-medium modifications of D and \bar{D} mesons has been studied in various approaches. For example, in the QCD sum rule approach, it is suggested that the light quark or antiquark of $D(\bar{D})$ mesons interacts with the light quark condensate leading to the medium modification of the $D(\bar{D})$ meson masses [30, 31]. The quark meson coupling model (QMC) has also been used to study the D-meson properties [32]. In the QMC model the scalar σ meson couples to the confined light quark (u,d) in the nucleon thus giving a drop of the nucleon mass in the medium. The drop in the mass of D mesons arises due to the interaction with the nuclear medium and the mass drop of D mesons observed in the QMC model turns out to be similar to that calculated in the QCD sum rule approach.

In the present investigation we study the properties of the D and \bar{D} mesons in the isospin-asymmetric hot nuclear matter. These modifications arise due to their interactions with the nucleons, the non-strange scalar isoscalar meson σ and the scalar isovector meson δ . The medium modifications of the light hadrons (nucleons and scalar mesons) are described by using a chiral $SU(3)$ model [33]. The model has been used to study finite nuclei, the nuclear matter properties, the in-medium properties of the vector mesons [40, 41] as well as to investigate the optical potentials of kaons and antikaons in nuclear matter [34, 35] and in hyperonic matter in [36]. For the study of the properties D mesons in isospin-asymmetric medium at finite temperatures, the chiral $SU(3)$ model is generalized to $SU(4)$ flavor symmetry to obtain the interactions of D and \bar{D} mesons with the light hadrons. The D meson properties in symmetric hot nuclear matter using the chiral effective model have been studied in ref. [42] and for the case of asymmetric nuclear matter at zero temperature in [43]. In a coupled channel approach for the study of D mesons, using a separable potential, it was shown that the resonance $\Lambda_c(2593)$ is generated dynamically in the $I=0$ channel [44] analogous to $\Lambda(1405)$ in the coupled channel approach for the $\bar{K}N$ interaction [45].

The approach has been generalized to study the spectral density of the D-mesons at finite temperatures and densities [46], taking into account the modifications of the nucleons in the medium. The results of this investigation seem to indicate a dominant increase in the width of the D-meson whereas there is only a very small change in the D-meson mass in the medium [46]. However, these calculations [44, 46], assume the interaction to be SU(3) symmetric in u,d,c quarks and ignore channels with charmed hadrons with strangeness. A coupled channel approach for the study of D-mesons has been developed based on SU(4) symmetry [47] to construct the effective interaction between pseudoscalar mesons in a 16-plet with baryons in 20-plet representation through exchange of vector mesons and with KSFR condition [48]. This model [47] has been modified in aspects like regularization method and has been used to study DN interactions in Ref. [49]. This reproduces the resonance $\Lambda_c(2593)$ in the $I=0$ channel and in addition generates another resonance in the $I=1$ channel at around 2770 MeV. These calculations have been generalized to finite temperatures [50] accounting for the in-medium modifications of the nucleons in a Walecka type $\sigma - \omega$ model, to study the D and \bar{D} properties [51] in the hot and dense hadronic matter. At the nuclear matter density and for zero temperature, these resonances ($\Lambda_c(2593)$ and $\Sigma_c(2770)$) are generated 45 MeV and 40 MeV below their free space positions. However at finite temperature, e.g., at $T = 100$ MeV resonance positions shift to 2579 MeV and 2767 MeV for Λ_c ($I = 0$) and Σ_c ($I = 1$) respectively. Thus at finite temperature resonances are seen to move closer to their free space values. This is because of the reduction of pauli blocking factor arising due to the fact that fermi surface is smeared out with temperature. For \bar{D} mesons in coupled channel approach a small repulsive mass shift is obtained. This will rule out of any possibility of charmed mesic nuclei [50] suggested in the QMC model [32]. But as we shall see in our investigation, we obtain a small attractive mass shift for \bar{D} mesons which can give rise to the possibility of the formation of charmed mesic nuclei. The study of D meson self-energy in the nuclear matter is also helpful in understanding the properties of the charm and the hidden charm resonances in the nuclear matter [52]. In coupled channel approach the charmed resonance $D_{s0}(2317)$ mainly couples to DK system, while the $D_0(2400)$ couples to $D\pi$ and $D_s\bar{K}$. The hidden charm resonance couples mostly to $D\bar{D}$. Therefore any modification of D meson properties in the nuclear medium will affect the properties of these resonances.

Within the effective chiral model considered in the present investigation, the $D(\bar{D})$ energies are modified due to a vectorial Weinberg-Tomozawa, scalar exchange terms (σ, δ) as well as range terms [35, 36]. The isospin asymmetric effects among D^0 and D^+ in the doublet, $D \equiv (D^0, D^+)$ as well as between \bar{D}^0 and D^- in the doublet, $\bar{D} \equiv (\bar{D}^0, D^-)$ arise due to the scalar-isovector δ meson, due to asymmetric contributions in the Weinberg-Tomozawa term, as well as in the range term [35].

We organize the paper as follows. In section II, we give a brief introduction to the effective chiral $SU(3)$ model used to study the isospin asymmetric nuclear matter at finite temperatures, and its extension to the chiral $SU(4)$ model to derive the interactions of the charmed mesons with the light hadrons. In section III, we present the dispersion relations for the D and \bar{D} mesons to be solved to calculate their optical potentials in the hot and dense hadronic matter. Section IV contains the results and discussions and finally, in section V, we summarize the results of present investigation and discuss possible outlook.

II. THE HADRONIC CHIRAL $SU(3) \times SU(3)$ MODEL

We use a chiral $SU(3)$ model for the study of the light hadrons in the present investigation [33]. The model is based on nonlinear realization of chiral symmetry [37, 38, 39] and broken scale invariance [33, 40, 41]. The effective hadronic chiral Lagrangian contains the following terms

$$\mathcal{L} = \mathcal{L}_{kin} + \sum_{W=X,Y,V,A,u} \mathcal{L}_{BW} + \mathcal{L}_{vec} + \mathcal{L}_0 + \mathcal{L}_{SB} \quad (1)$$

In Eq.(1), \mathcal{L}_{kin} is the kinetic energy term, \mathcal{L}_{BW} is the baryon-meson interaction term in which the baryons-spin-0 meson interaction term generates the baryon masses. \mathcal{L}_{vec} describes the dynamical mass generation of the vector mesons via couplings to the scalar mesons and contain additionally quartic self-interactions of the vector fields. \mathcal{L}_0 contains the meson-meson interaction terms inducing the spontaneous breaking of chiral symmetry as well as a scale invariance breaking logarithmic potential. \mathcal{L}_{SB} describes the explicit chiral symmetry breaking.

To study the hadron properties in the present investigation we use the mean field approximation and frozen glue ball limit. The scalar gluon condensate of QCD is simulated by a

scalar dilaton field in the present hadronic model. Since the gluon condensate is known to have a very marginal dependence on the changes in the density, in the present investigation, we take the expectation value of the dilaton field to be constant [33]. This is called the frozen glue ball approximation. We solve the coupled equations of motion by minimizing the thermodynamic potential and obtain the expectation values of the meson fields. At finite temperatures, the vector and scalar densities for the baryons are given as

$$\begin{aligned}\rho_i &= \gamma_i \int \frac{d^3k}{(2\pi)^3} (f_i(k) - \bar{f}_i(k)) \\ \rho_i^s &= \gamma_i \int \frac{d^3k}{(2\pi)^3} \frac{m_i^*}{E_i^*} (f_i(k) + \bar{f}_i(k))\end{aligned}\quad (2)$$

where $f_i(k)$ and $\bar{f}_i(k)$ are the thermal distribution functions for the baryon and antibaryon of species i [35] and $\gamma_i=2$ is the spin degeneracy factor.

III. D AND \bar{D} MESONS IN THE HOT ASYMMETRIC NUCLEAR MATTER

In this section we study the D and \bar{D} mesons properties in isospin-asymmetric nuclear matter at finite temperatures. The medium modifications of the D and \bar{D} mesons arise due to their interactions with the nucleons and the scalar mesons and the interaction Lagrangian density is given as [43]

$$\begin{aligned}\mathcal{L}_{\mathcal{DN}} &= -\frac{i}{8f_D^2} \left[3(\bar{p}\gamma^\mu p + \bar{n}\gamma^\mu n) \left(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0 \right) + \left(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^- \right) \right. \\ &\quad \left. + (\bar{p}\gamma^\mu p - \bar{n}\gamma^\mu n) \left(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0 \right) - \left(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^- \right) \right] \\ &\quad + \frac{m_D^2}{2f_D^2} \left[(\sigma + \sqrt{2}\zeta_c)(\bar{D}^0 D^0 + (D^- D^+)) + \delta(\bar{D}^0 D^0) - (D^- D^+) \right] \\ &\quad - \frac{1}{f_D} \left[(\sigma + \sqrt{2}\zeta_c) \left((\partial_\mu \bar{D}^0)(\partial^\mu D^0) + (\partial_\mu D^-)(\partial^\mu D^+) \right) \right. \\ &\quad \left. + \delta \left((\partial_\mu \bar{D}^0)(\partial^\mu D^0) - (\partial_\mu D^-)(\partial^\mu D^+) \right) \right] \\ &\quad + \frac{d_1}{2f_D^2} (\bar{p}p + \bar{n}n) \left((\partial_\mu D^-)(\partial^\mu D^+) + (\partial_\mu \bar{D}^0)(\partial^\mu D^0) \right) \\ &\quad + \frac{d_2}{4f_D^2} \left[(\bar{p}p + \bar{n}n) \left((\partial_\mu \bar{D}^0)(\partial^\mu D^0) + (\partial_\mu D^-)(\partial^\mu D^+) \right) \right. \\ &\quad \left. + (\bar{p}p - \bar{n}n) \left((\partial_\mu \bar{D}^0)(\partial^\mu D^0) - (\partial_\mu D^-)(\partial^\mu D^+) \right) \right]\end{aligned}\quad (3)$$

In Eq.(3), the first term is the vectorial Weinberg Tomozawa interaction term, obtained from the kinetic term of Eq.(1). The second term is obtained from the explicit symmetry breaking

term and leads to the attractive interactions for both the D and \bar{D} mesons in the medium. The next three terms of above Lagrangian density ($\sim (\partial_\mu \bar{D})(\partial^\mu D)$) are known as the range terms. The first range term (with coefficient $(-\frac{1}{f_D})$) is obtained from the kinetic energy term of the pseudoscalar mesons. The second and third range terms d_1 and d_2 are written for the DN interactions in analogy with those written for KN interactions in [36]. It might be noted here that the interaction of the pseudoscalar mesons with the vector mesons, in addition to the pseudoscalar meson-nucleon vectorial interaction, leads to a double counting in the linear realization of chiral effective theories. Further, in the non-linear realization, such an interaction does not arise in the leading or subleading order, but only as a higher order contribution [53]. Hence the vector meson-pseudoscalar interactions will not be taken into account in the present investigation.

The dispersion relations for the D and \bar{D} mesons are obtained by the Fourier transformations of equations of motion. These are given as

$$-\omega^2 + \vec{k}^2 + m_D^2 - \Pi(\omega, |\vec{k}|) = 0 \quad (4)$$

where, m_D is the vacuum mass of the $D(\bar{D})$ meson and $\Pi(\omega, |\vec{k}|)$ denotes the self-energy of the $D(\bar{D})$ mesons in the medium.

The self-energy $\Pi(\omega, |\vec{k}|)$ for the D meson doublet (D^0, D^+) arising from the interaction of Eq.(3) is given as

$$\begin{aligned} \Pi(\omega, |\vec{k}|) = & \frac{1}{4f_D^2} [3(\rho_p + \rho_n) \pm (\rho_p - \rho_n)] \omega \\ & + \frac{m_D^2}{2f_D} (\sigma' + \sqrt{2}\zeta_c' \pm \delta') \\ & + \left[-\frac{1}{f_D} (\sigma' + \sqrt{2}\zeta_c' \pm \delta') + \frac{d_1}{2f_D^2} (\rho_s^p + \rho_s^n) \right. \\ & \left. + \frac{d_2}{4f_D^2} ((\rho_s^p + \rho_s^n) \pm (\rho_s^p - \rho_s^n)) \right] (\omega^2 - \vec{k}^2), \end{aligned} \quad (5)$$

where the \pm signs refer to the D^0 and D^+ mesons, respectively, and $\sigma'(\sigma - \sigma_0)$, $\zeta_c'(\zeta_c - \zeta_{c0})$, and $\delta'(\delta - \delta_0)$ are the fluctuations of the scalar isoscalar fields σ and ζ and the scalar-isoscalar field δ from their vacuum expectation values. The vacuum expectation value of δ is zero ($\delta_0 = 0$), since a nonzero value for it will break the isospin-symmetry of the vacuum. (We neglect here the small isospin breaking effect arising from the mass and

charge difference of the up and down quarks.) We might note here that the interaction of the scalar quark condensate ζ_c (being made up of heavy charmed quarks and antiquarks) leads to very small modifications of the masses [55]. So we will not consider the medium fluctuations of ζ_c . In Eq. (5), ρ_p and ρ_n are the number densities of protons and neutrons and ρ_p^s and ρ_n^s are their scalar densities, as given by equation (2).

Similarly, for the \bar{D} meson doublet (\bar{D}^0, D^-) , the self-energy is calculated as

$$\begin{aligned} \Pi(\omega, |\vec{k}|) = & -\frac{1}{4f_D^2} [3(\rho_p + \rho_n) \pm (\rho_p - \rho_n)] \omega \\ & + \frac{m_D^2}{2f_D} (\sigma' + \sqrt{2}\zeta_c' \pm \delta') \\ & + \left[-\frac{1}{f_D} (\sigma' + \sqrt{2}\zeta_c' \pm \delta') + \frac{d_1}{2f_D^2} (\rho_p^s + \rho_n^s) \right. \\ & \left. + \frac{d_2}{4f_D^2} ((\rho_p^s + \rho_n^s) \pm (\rho_p^s - \rho_n^s)) \right] (\omega^2 - \vec{k}^2), \end{aligned} \quad (6)$$

where the \pm signs refer to the \bar{D}^0 and D^- mesons, respectively. The optical potentials of the D and \bar{D} mesons are obtained using the expression

$$U(\omega, k) = \omega(k) - \sqrt{k^2 + m_D^2} \quad (7)$$

where m_D is the vacuum mass for the $D(\bar{D})$ meson and $\omega(k)$ is the momentum-dependent energy of the $D(\bar{D})$ meson.

IV. RESULTS AND DISCUSSIONS

In this section we present the results and discussions of our investigation of the in-medium properties of D and \bar{D} mesons in isospin asymmetric nuclear matter at finite temperatures. We have generalized the chiral $SU(3)$ model to $SU(4)$ to include the interactions of the charmed mesons. The present calculations use the following model parameters. The values, $g_{\sigma N} = 10.6$ and $g_{\zeta N} = -0.47$ are determined by fitting vacuum baryon masses. The other parameters fitted to the asymmetric nuclear matter saturation properties in the mean-field approximation are: $g_{\omega N} = 13.3$, $g_{\rho N} = 5.5$, $g_4 = 79.7$, $g_{\delta N} = 2.5$, $m_\zeta = 1024.5$ MeV, $m_\sigma = 466.5$ MeV and $m_\delta = 899.5$ MeV. The coefficients d_1 and d_2 , calculated from the empirical values of the KN scattering lengths for $I = 0$ and $I = 1$ channels, are $2.56/m_K$ and $0.73/m_K$, respectively [36].

In isospin asymmetric nuclear medium, the properties of the D mesons (D^+ , D^0) and \bar{D} mesons (D^- , \bar{D}^0), due to their interactions with the hot hadronic medium, undergo medium modifications. These modifications arise due to the interactions with the nucleons (through the Weinberg-Tomozawa vectorial interaction as well as through the range terms) and the scalar exchange terms. The modifications of the scalar mean fields modify the masses of the nucleons in the hot and dense hadronic medium. Before going into the details of how the D and \bar{D} mesons properties are modified at finite temperatures in the dense nuclear medium, let us see how the scalar fields are modified at finite temperatures in the nuclear medium. In figure 1, we plot the variations of σ and ζ with temperature at zero baryon density. We observe that the magnitudes of the scalar fields σ and ζ decrease with increase in temperature. However, the drop in their magnitudes with temperature is negligible upto a temperature of about 100 MeV (that is, they remain very close to their vacuum values). The changes in the magnitudes of the σ and ζ fields are 2.5 MeV and 0.8 MeV respectively, when the temperature changes from 100 MeV to 150 MeV, above which the drop increases. These values change to about 10 MeV and 3 MeV for the σ and ζ fields respectively, for a change in temperature of 100 MeV to 175 MeV.

We plot the temperature dependence of the σ and ζ fields for baryon densities $\rho_B = \rho_0$ and $\rho_B = 4\rho_0$ in figures 2 and 3 respectively. At finite values of densities, the magnitudes of the scalar fields σ and ζ first increase with increase in temperature upto a certain value after which they start decreasing. For example, at $\rho_B = \rho_0$, and for the value of the isospin asymmetry parameter, $\eta = 0$ the scalar fields σ and ζ increase with temperature upto a temperature of about 150 MeV and after they both start decreasing. At $\eta = 0.5$ the value of temperature upto which these scalar fields increase becomes about 120 – 125 MeV. For $\rho_B = 4\rho_0$ and $\eta = 0$ the scalar field σ and ζ fields increase upto a temperature of about 160 MeV. At $\eta = 0.5$ this value of temperature is lowered to 120 MeV and 135 MeV for σ and ζ respectively. This observed rise in the magnitudes of σ and ζ fields with temperature leads to an increase in the mass of nucleons with temperature at finite densities. Such a behaviour of nucleon mass with temperature at finite baryon densities was also observed within chiral $SU(3)$ model in [41] and within Walecka model by Ko and Li in [8].

We study the density dependence of D and \bar{D} masses at finite temperatures at selected

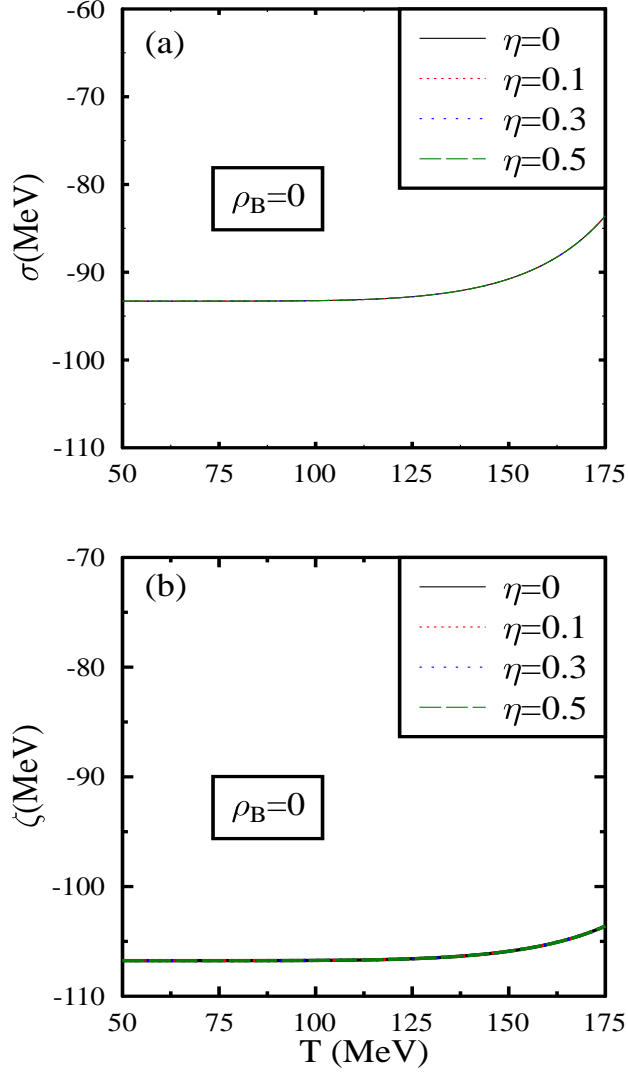


FIG. 1: (Color online) Scalar fields σ and ζ versus temperature for baryon density $\rho_B = 0$.

values of the isospin asymmetric parameter, η and compare the results with the zero temperature case [43]. In Fig. 4, we show the variation of the energy of the D mesons (D^+ , D^0) at zero momentum with baryon density ρ_B for different values of isospin asymmetry parameter η and with the values of temperature as $T = 0, 100, 150$ MeV. The isospin-asymmetry in the medium is seen to give an increase in the D^0 mass and a drop in the D^+ mass as compared to the isospin symmetric ($\eta = 0$) case. This is observed both for zero temperature [43] and

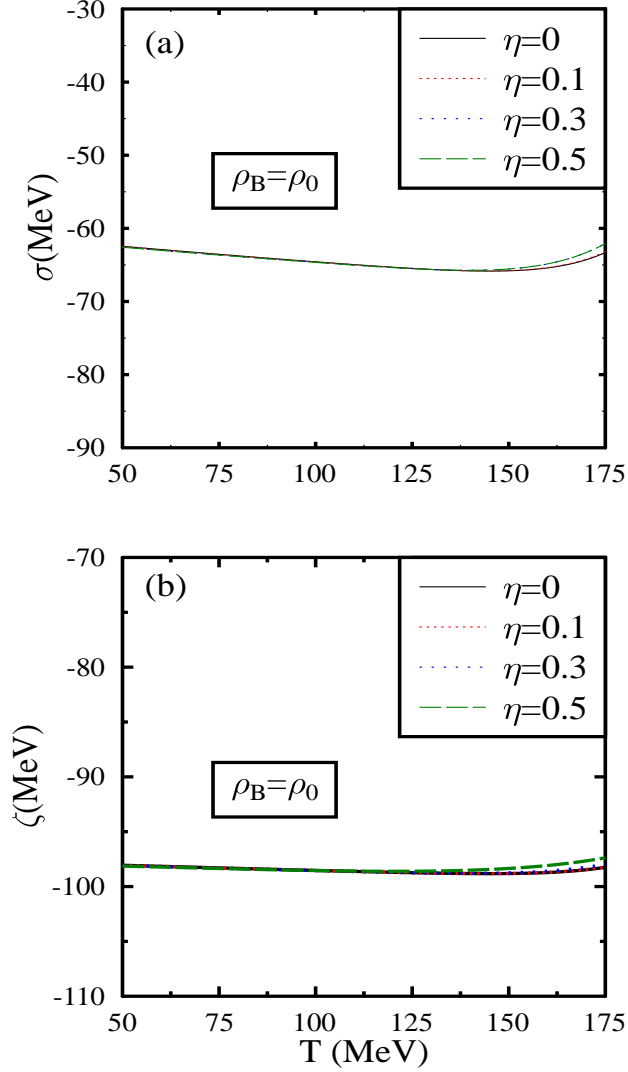


FIG. 2: (Color online) Scalar fields σ and ζ versus temperature for density $\rho_B = \rho_0$ and isospin asymmetric parameter η as 0, 0.1, 0.3 and 0.5.

finite temperature cases. At nuclear matter saturation density, $\rho_B = \rho_0$, the drop in the mass of D^+ meson from its vacuum value (1869 MeV) is 81 MeV for zero temperature case in isospin symmetric medium. At a density of $4\rho_0$, this drop in the mass of D^+ meson is seen to be about 364 MeV for $\eta=0$. At finite temperatures, the drop in the mass of D^+ meson for a given value of isospin asymmetry decreases as compared to the zero temperature case.

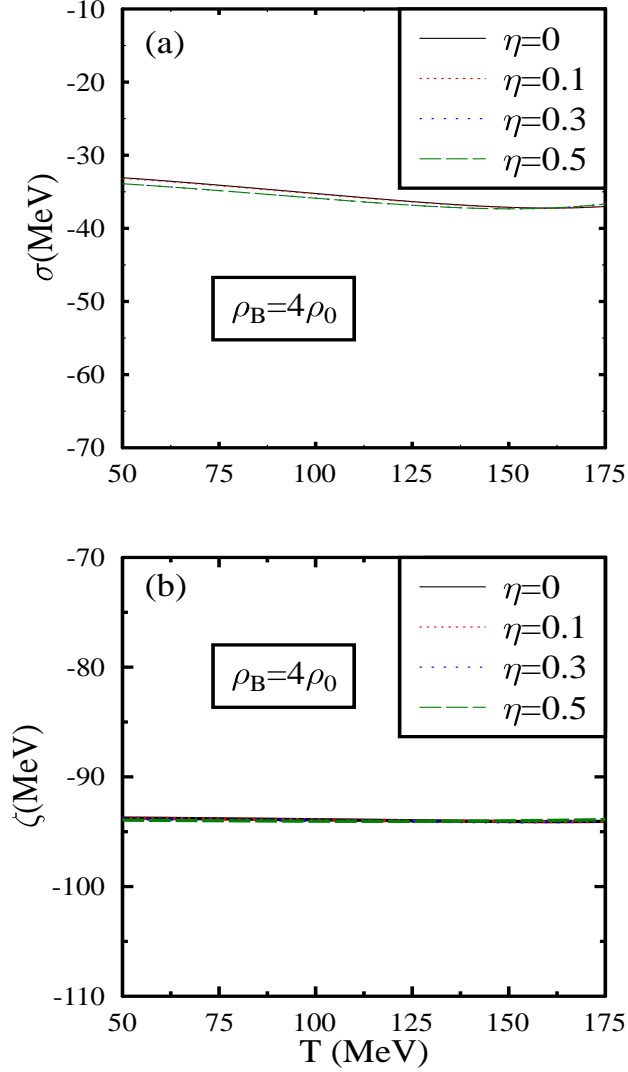


FIG. 3: (Color online) Scalar fields σ and ζ versus temperature for density $\rho_B = 4 \rho_0$ and isospin asymmetric parameter η as 0, 0.1, 0.3 and 0.5.

For example, at nuclear saturation density, ρ_0 , the drop in the mass of D^+ meson turns out to be 74, 67 and 63 MeV at a temperature of $T = 50, 100$ and 150 MeV respectively for the isospin symmetric matter. At a higher density of $\rho_B = 4\rho_0$, zero temperature value for the D^+ drop of about 364 MeV is modified to 352, 327 and 307 MeV for $T = 50, 100$ and 150 MeV respectively. Thus the masses of D mesons at finite temperatures and finite densities

are observed to be larger than the values at zero temperature case. This is because of the increase in the magnitudes of the scalar fields σ and ζ with temperature at finite densities as mentioned earlier. The same behaviour remains for the isospin asymmetric matter. This behaviour of the nucleons and hence of the D-mesons with temperature was also observed earlier for symmetric nuclear matter at finite temperatures within the chiral effective model [42]. The drop in the mass of D^+ meson is seen to be larger as we increase the value of the isospin asymmetry parameter. We observe that as we change η from 0 to 0.5, then the drop in the mass of D^+ meson is 97 MeV and 397 MeV at densities of ρ_0 and $4\rho_0$ respectively, for the zero temperature case. At $T = 50$ MeV these values change to 91 MeV at ρ_0 and 389 MeV at a density of $4\rho_0$. At $T = 150$ MeV the drop in the mass of D^+ is 85 MeV at ρ_0 and 369 MeV at $4\rho_0$. Thus we observe that for a given value of density, as we move from $\eta = 0$ to $\eta = 0.5$ the drop in mass of D^+ mesons is lower at higher temperatures.

The mass of the D^0 meson drops with density as can be seen from figure 4. The drop in the mass of D^0 meson at density ρ_0 from its vacuum value (1864.5 MeV) is 80, 73.5, 66.5, 63 MeV for temperature $T = 0, 50, 100, 150$ MeV respectively at $\eta = 0$. At density $4\rho_0$ and isospin-asymmetry parameter $\eta = 0$, these values become 361, 348.5, 324 and 304 MeV for temperatures $T=0, 50, 100$ and 150 MeV respectively. For the D^0 meson, there is seen to be an increase in the mass as we move from isospin symmetric to isospin asymmetric medium. For example, at zero temperature and baryon density equal to ρ_0 and $4\rho_0$, the rise in the masses of the D^0 meson are 21 and 91 MeV respectively as we move from isospin-symmetric medium ($\eta = 0$) to isospin-asymmetric medium ($\eta = 0.5$). At a temperature of 50 MeV, these values become 19 MeV at ρ_0 and 85 MeV at $4\rho_0$. For $T=150$ MeV, these values become 9 MeV at ρ_0 and 43.5 MeV at $4\rho_0$. Thus for D^0 mesons, the rise in the mass, is seen to be lowered at higher temperatures as we move from $\eta = 0$ to $\eta = 0.5$.

Fig.5 shows the results for the density dependence of the energies of the \bar{D} mesons at zero momentum at values of the temperature, $T = 0, 100, 150$ MeV. There is seen to be a drop of the masses of both the D^- and \bar{D}^0 with density. This is due to the dominance of the attractive scalar exchange contribution as well as the range terms (which becomes attractive above a density of about 2-2.5 times the nuclear matter saturation density) over the repulsive Weinberg-Tomozawa interaction [43]. It is observed that the drop in the mass

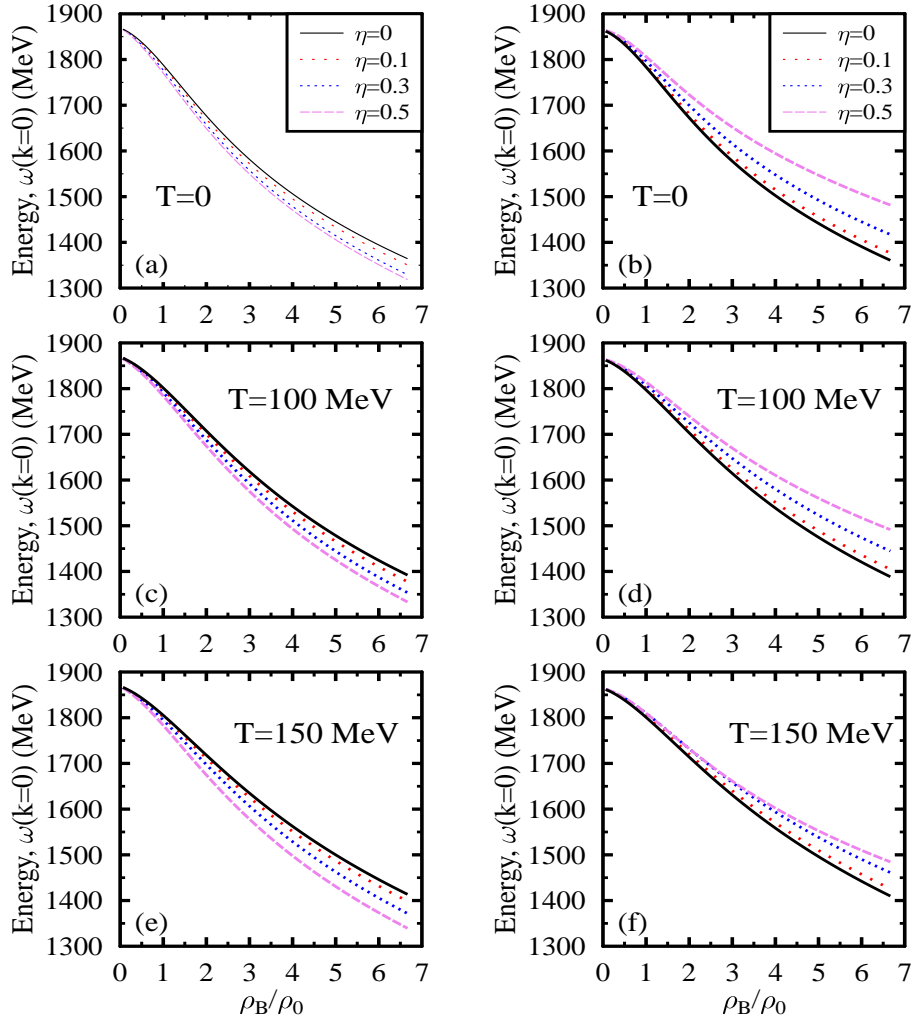


FIG. 4: (Color online) The energies of D^+ meson ((a),(c) and (e)) and of D^0 meson ((b),(d) and (f)), at momentum $k = 0$, versus the baryon density (in units of nuclear saturation density), ρ_B/ρ_0 , for different values of the isospin asymmetry parameter ($\eta = 0, 0.1, 0.3, 0.5$) and for given values of temperature ($T = 0, 100$ MeV and 150 MeV).

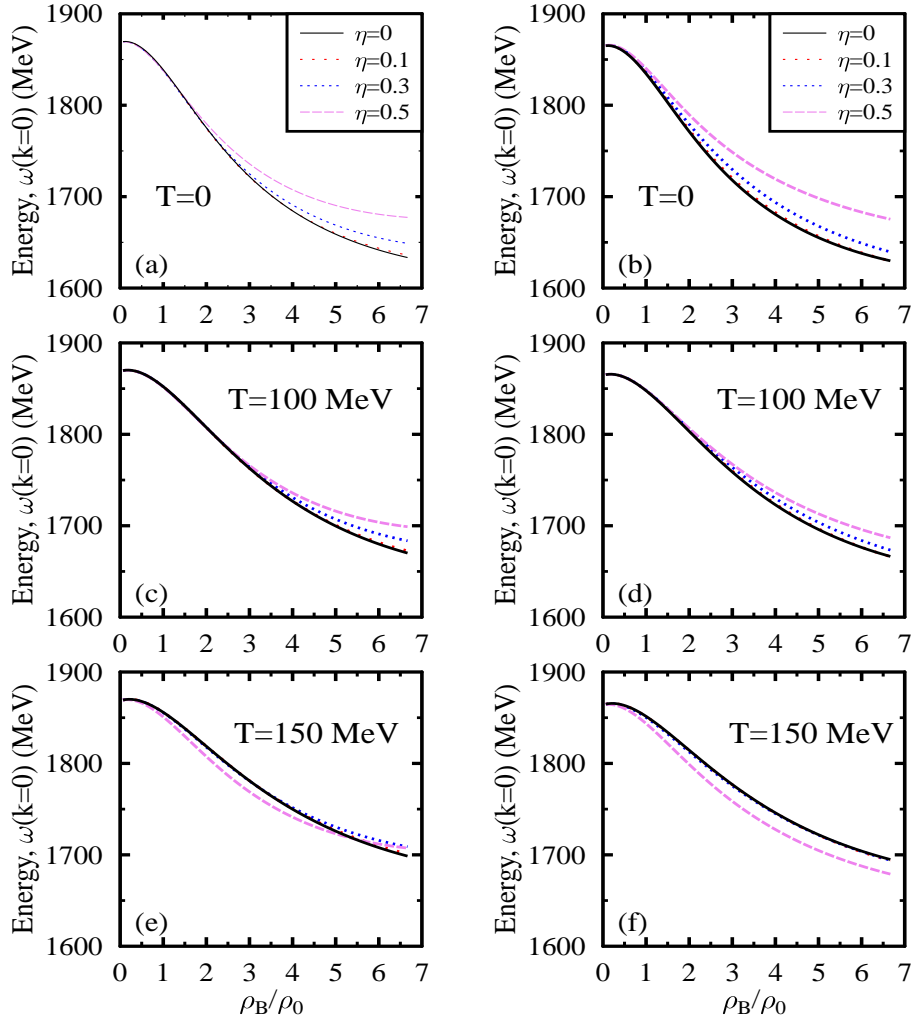


FIG. 5: (Color online) The energies of D^- meson ((a),(c) and (e)) and of \bar{D}^0 meson ((b),(d) and (f)), at momentum $k = 0$, versus the baryon density, expressed in units of nuclear saturation density, ρ_B/ρ_0 , for different values of the isospin asymmetry parameter ($\eta = 0, 0.1, 0.3, 0.5$) and for given values of temperature ($T = 0, 100$ MeV and 150 MeV).

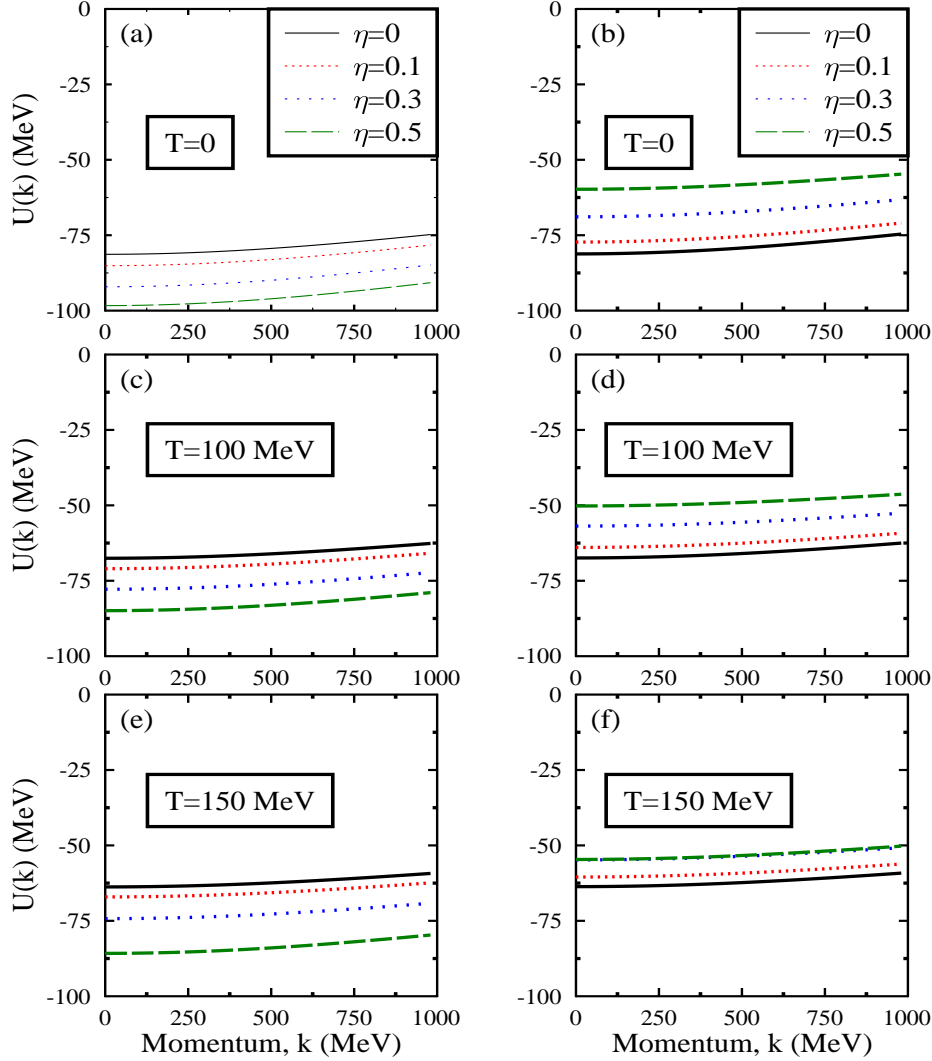


FIG. 6: (Color online) The optical potential of D^+ meson (a,c and e) and of D^0 meson (b,d and f), are plotted as functions of momentum for $\rho_B = \rho_0$, for different values of the isospin asymmetry parameter ($\eta = 0, 0.1, 0.3, 0.5$) and for given values of temperature ($T = 0, 100$ MeV and 150 MeV).

of D^- (\bar{D}^0) in isospin symmetric nuclear matter is 30 (29.5) MeV at ρ_0 and 184 (183) at $4\rho_0$, at zero temperature, from their vacuum values. As we go to higher temperatures, the drop in the masses of D^- and \bar{D}^0 mesons decreases. For example, at $\eta = 0$ and $\rho_B = \rho_0$ the drop in the mass of D^- meson is 23, 16 and 12 MeV at a temperature of 50, 100 and 150 MeV

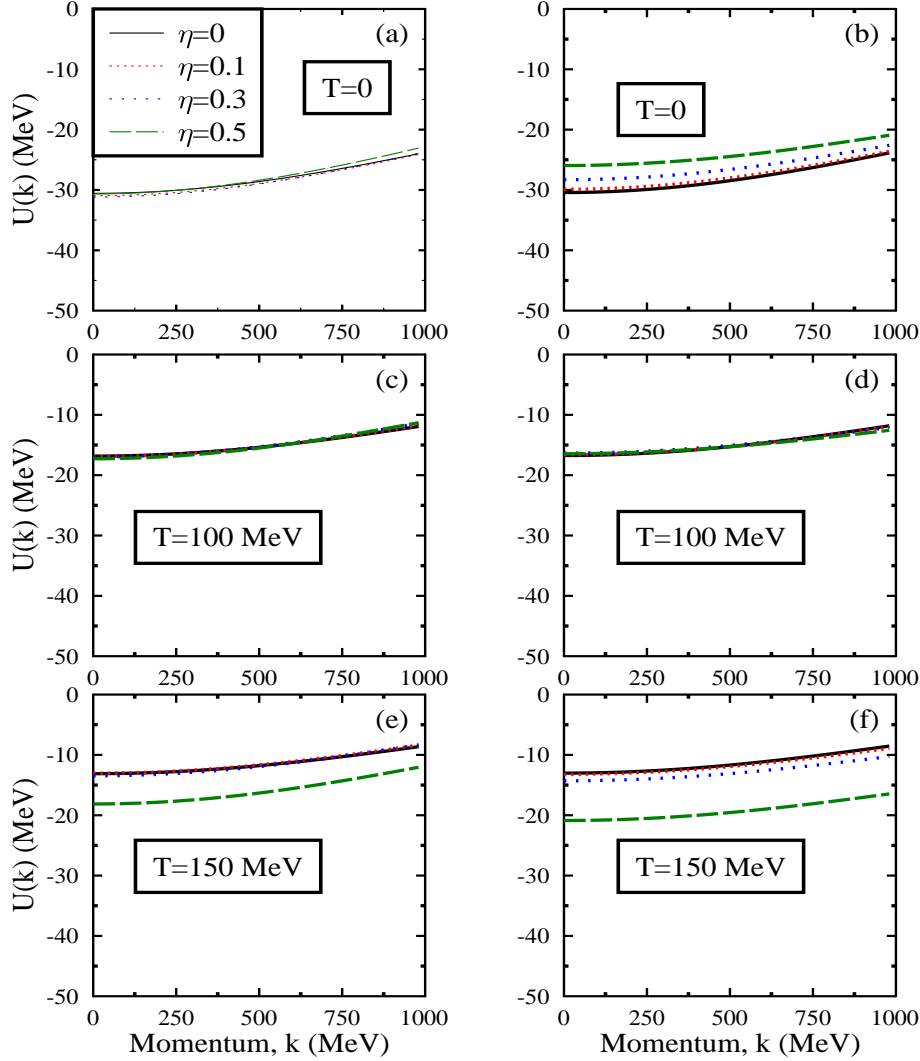


FIG. 7: (Color online) The optical potential of D^- meson (a,c and e) and of \bar{D}^0 meson (b,d and f), are plotted as functions of momentum for $\rho_B = \rho_0$, for different values of the isospin asymmetry parameter ($\eta = 0, 0.1, 0.3, 0.5$) and for given values of temperature ($T = 0, 100$ MeV and 150 MeV).

respectively. The masses of D^- and \bar{D}^0 mesons are seen to have negligible dependence on the isospin asymmetry upto a density of $\rho_B = \rho_0$. However, at high densities there is seen to be appreciable dependence of these masses on the parameter, η . For example, at a baryon density of $4\rho_0$ and $\eta = 0$, the drop in the mass of the D^- meson is 169, 140.5 and 117.5 MeV

for $T = 50, 100$ and 150 MeV respectively. But at $\eta = 0.5$, these values change to $150, 131$ and 126 MeV for $T = 50, 100$ and 150 MeV respectively. It is seen that, at high densities there is an increase in the masses of both D^- and \bar{D}^0 mesons in isospin asymmetric medium as compared to those in the isospin symmetric nuclear matter for temperatures $T=0, 50$ and 100 MeV. However, at $T = 150$ MeV, it is observed that for densities upto about $5\rho_0$, the mass of D^- meson is higher in the isospin symmetric matter as compared to in the isospin asymmetric matter with $\eta = 0.5$. It is also seen that the modifications in the masses of D^- mesons is negligible as we change η from 0 to 0.3 upto a density of about $4\rho_0$. For the \bar{D}^0 meson, one sees that the isospin dependence is negligible upto $\eta=0.3$ and the mass is lowered for $\eta=0.5$ as compared to the mass in symmetric nuclear matter. The drop in the mass of \bar{D}^0 mesons is 8 MeV and 18 MeV at ρ_0 and $4\rho_0$ respectively. For \bar{D}^0 mesons also there is seen to be negligible change in mass as we change the asymmetry parameter η from 0 upto 0.3 . This is because the drop in the mass of \bar{D}^0 mesons given by Weinberg-Tomozawa term almost cancel with the increase due to the scalar and range terms as we go from $\eta = 0$ to $\eta = 0.3$. At zero temperature [43] as well as for temperatures $T=50$ and 100 MeV, there is increase in the mass of the \bar{D} mesons (D^-, \bar{D}^0) as we go from isospin symmetric medium to the isospin asymmetric medium. This is because for $T=0, 50$ and 100 MeV, the increase in mass of \bar{D} given by the scalar exchange and the range terms were dominating over the drop given by the Weinberg Tomozawa term as we go from symmetric nuclear medium ($\eta = 0$) to isospin asymmetric nuclear medium ($\eta = 0.1, 0.3, 0.5$). However, at $T = 150$ MeV, for $\eta = 0.5$, the drop given by Weinberg term dominates over the rise given by scalar and range terms for \bar{D}^0 and upto a density of about $5\rho_0$ for D^- , and therefore mass of \bar{D} mesons decreases as we go from symmetric nuclear medium to isospin asymmetric nuclear medium in these density regimes.

Figures 6 and 8 show the isospin dependence of the optical potentials for the D mesons as functions of the momentum, for densities ρ_0 and $4\rho_0$ respectively and for values of the temperature as $T = 0, 100, 150$ MeV. Figures 7 and 9 illustrate the optical potentials for the \bar{D} doublet. The isospin dependence of optical potentials is seen to be quite significant for high densities for the D -meson doublet (D^+, D^0) as compared to those for the \bar{D} doublet. This is a reflection of the strong isospin dependence of the masses of the D -mesons as

compared to the \bar{D} as has been already illustrated in figures 4 and 5. For the \bar{D} mesons, it is seen, from figure 5, that the masses of the D^- meson and \bar{D}^0 meson for a fixed value of the isospin asymmetry parameter, η are very similar, an observation which was seen earlier for the zero temperature case [43]. These are reflected in their optical potentials, plotted in figures 7 and 9, where one sees a maximum difference of about 5 MeV or so between D^- and \bar{D}^0 for $\rho_B = \rho_0$ and about 10 – 15 MeV for $\rho_B = 4\rho_0$. The present investigations of the optical potentials for the D and \bar{D} mesons show a much stronger dependence of isospin asymmetry on the D meson doublet, as compared to that in the \bar{D} meson doublet, as was already observed for the zero temperature case. The medium modifications of the masses of D and \bar{D} mesons can lead to the explanation of J/ψ suppression observed by NA50 collaboration at 158 GeV/nucleon in the Pb-Pb collisions [20]. Due to the drop in the mass of the $D\bar{D}$ pair in the nuclear medium, it can become a possibility that the excited states of charmonium ($\psi', \chi_{c2}, \chi_{c1}, \chi_{c0}$) can decay to $D\bar{D}$ [43] and hence the production of J/Ψ from the decay of these excited states can be suppressed. Even at high values of densities at given temperatures, it can become a possibility that J/ψ itself decays to $D\bar{D}$ pairs. Thus the medium modifications of the D mesons can change the decay widths of the charmonium states [29].

The decay of the charmonium states have been studied in Ref. [25, 29]. It is seen to depend sensitively on the relative momentum in the final state. These excited states might become narrow [29] though the D meson mass is decreased appreciably at high densities. It may even vanish at certain momentum corresponding to nodes in the wave function [29]. Though the decay widths for these excited states can be modified by their wave functions, the partial decay width of χ_{c2} , owing to absence of any nodes, can increase monotonically with the drop of the D^+D^- pair mass in the medium. This can give rise to depletion in the J/Ψ yield in heavy-ion collisions. The dissociation of the quarkonium states ($\Psi', \chi_c, J/\Psi$) into $D\bar{D}$ pairs has also been studied [54, 56] by comparing their binding energies with the lattice results on the temperature dependence of the heavy-quark effective potential [57].

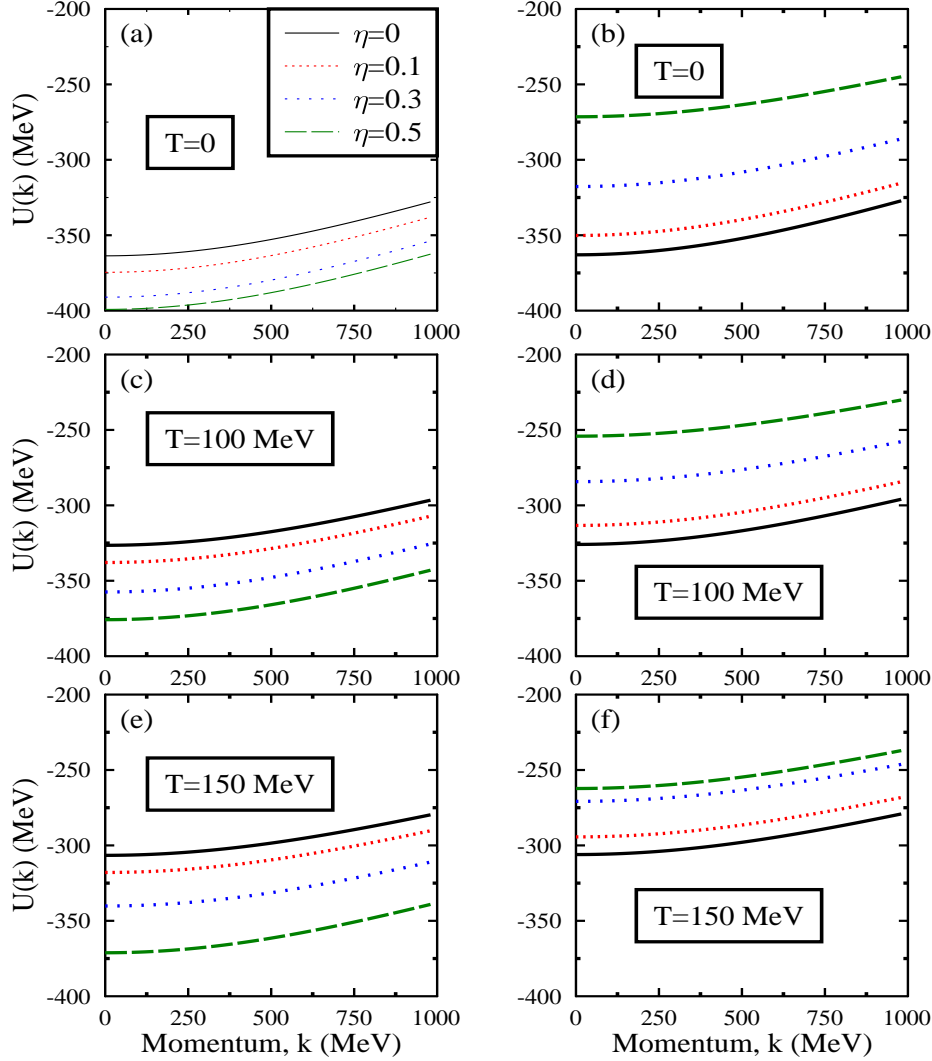


FIG. 8: (Color online) The optical potential of D^+ meson (a,c and e) and of D^0 meson (b,d and f), are plotted as functions of momentum for $\rho_B = 4\rho_0$, for different values of the isospin asymmetry parameter ($\eta = 0, 0.1, 0.3, 0.5$) and for given values of temperature ($T = 0, 100$ MeV and 150 MeV).

V. SUMMARY

We have investigated in a chiral model the in-medium masses of the D , \bar{D} mesons in hot isospin asymmetric nuclear matter, arising from their interactions with the nucleons and the

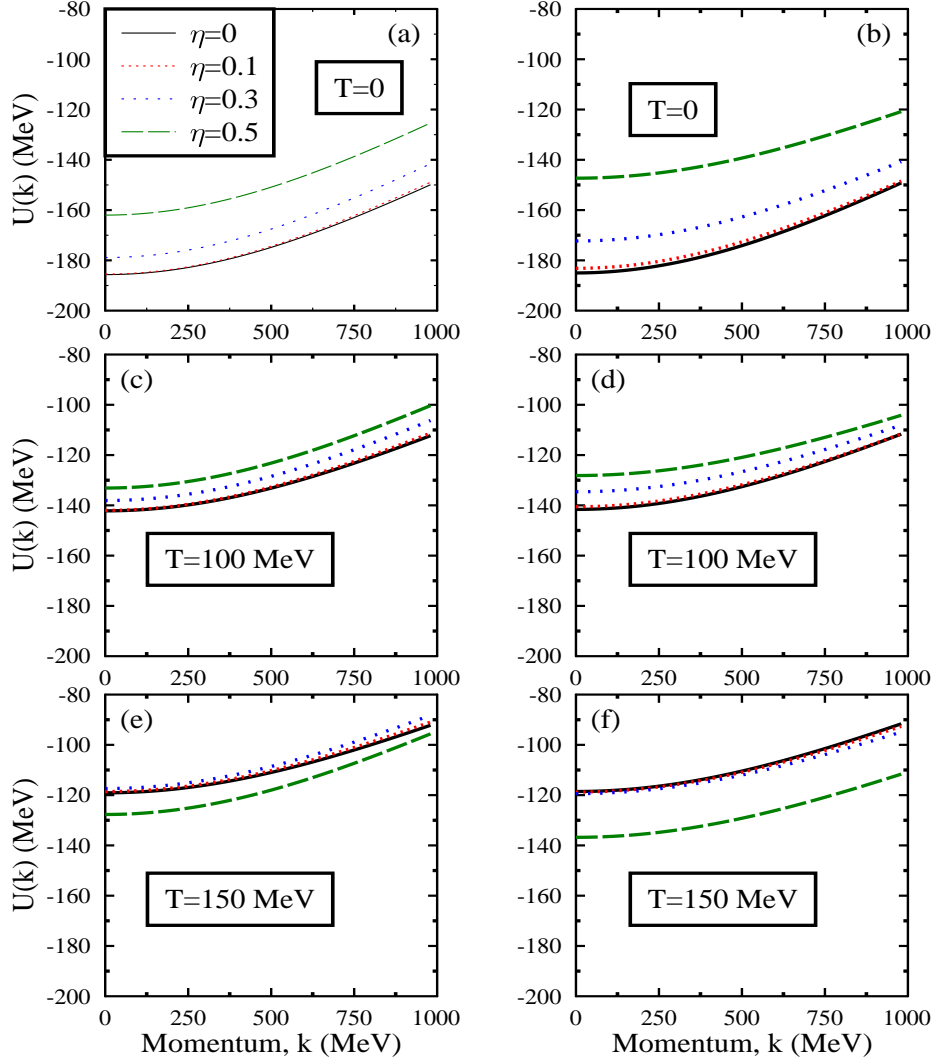


FIG. 9: (Color online) The optical potential of D^- meson (a,c and e) and of \bar{D}^0 meson (b,d and f), are plotted as functions of momentum for $\rho_B = 4\rho_0$, for different values of the isospin asymmetry parameter ($\eta = 0, 0.1, 0.3, 0.5$) and for given values of temperature ($T = 0, 100$ MeV and 150 MeV).

scalar mesons. The properties of the light hadrons – as studied in $SU(3)$ chiral model – modify the $D(\bar{D})$ meson properties in the dense and hot hadronic matter. The $SU(3)$ model, with parameters fixed from the properties of the hadron masses in vacuum and low-energy KN scattering data, is extended to $SU(4)$ to drive the interactions of $D(\bar{D})$ mesons with the

light hadron sector. The mass modifications of D^+ and D^0 mesons is strongly dependent on isospin-asymmetry of medium. The mass of D mesons observed at finite temperature is more as compared to zero temperature case because of less decrease of scalar fields at finite temperature and finite densities. This is in accordance with earlier work on D mesons modifications in symmetric nuclear matter at finite temperature [42]. The mass modification for the D mesons are seen to be similar to earlier finite density calculations of QCD sum rules [31, 58] as well as to the quark-meson coupling model [32], in contrast to the small mass modifications in the coupled channel approach [46, 50]. Also we obtained small attractive mass shifts for \bar{D} mesons in contrast with coupled channel approach [50]. These attractive potentials for \bar{D} mesons are in favor of charmed mesic nuclei. In our calculations the presence of the repulsive first range term (with coefficient $-\frac{1}{f_D}$ in Eq. (3)) is compensated by the attractive d_1 and d_2 terms in Eq.(3). Among attractive d_1 and d_2 terms, d_1 term is found to be dominating over d_2 term.

The medium modifications of the D meson masses can lead to a suppression in the J/Ψ yield in heavy-ion collisions, since the excited states of the J/Ψ ($\simeq 5\rho_0$), J/Ψ , can decay to $D\bar{D}$ pairs in the dense hadronic medium. The decay to the D^+D^- pairs seems to be insensitive at zero temperature but at high temperature like 150 MeV these decay become sensitive to isospin asymmetry of the medium. The isospin asymmetry lowers the density at which decay to D^+D^- pairs occur. Due to increase in the mass of $D^0\bar{D}^0$ in the isospin-asymmetric medium, isospin-asymmetry is seen to disfavor the decay of the charmonium states to the $D^0\bar{D}^0$ pairs. At a finite temperature there does not seem to be the possibility of decay of J/Ψ to $D^0\bar{D}^0$ pairs. The isospin dependence of D^+ and D^0 masses is seen to be a dominant medium effect at high densities, which might show in their production (D^+/D^0), whereas, for the D^- and \bar{D}^0 , one sees that, even though these have a strong density dependence, their in-medium masses remain similar at a given value for the isospin-asymmetry parameter η . The strong density dependence as well as the isospin dependence of the $D(\bar{D})$ meson optical potentials in asymmetric nuclear matter can be tested in the asymmetric heavy-ion collision experiments at future GSI facility [16]. In this work we considered only nucleons. The study of the in-medium modifications of D mesons in hyperonic matter along with nucleons at zero and finite temperatures within the

chiral $SU(4)$ model, and the study of in-medium properties of the charmonia states in the hot asymmetric hadronic matter, due to their interactions with the D-mesons as well as interactions to the dilaton field associated with the broken scale invariance (related to the gluon condensates) will be possible extensions of the present investigation.

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